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This chapter provides introductory material on three-dimensional synthetic environments. Readers are given an understanding of what synthetic environments are and how they are used in varied disciplines along with a look at some of the technologies used for synthetic environment visualization. Readers are provided with an outline of the sources and nature of synthetic environment data and are presented with the challenges associated with constructing realistic synthetic environments.

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Chapter #

An Overview of 3D Synthetic Environment Construction

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Key words: 3D Synthetic Environment, Virtual Reality, 3D-Spatial Database, Vector Product Format

Abstract: This chapter provides introductory material on three-dimensional synthetic environments. Readers are given an understanding of what synthetic environments are and how they are used in varied disciplines along with a look at some of the technologies used for synthetic environment visualization. Readers are provided with an outline of the sources and nature of synthetic environment data and are presented with the challenges associated with constructing realistic synthetic environments.

1. INTRODUCTION

A common conception of *Three-Dimensional Synthetic Environments* (3D SEs) is that of traditional military modeling and simulation (M&S) in which a digital simulation of the natural environment is provided for rehearsal of military operations. However, the use of 3D SEs has grown well beyond M&S to many diverse disciplines such as city planning [Koninger 98, Liggett 95, Tempfli 97], surgical training [Ota 98], manufacturing [Schmeider 98] and education [VETL 98]. In contrast to M&S applications, for example, 3D SEs of the human body are being used to train surgeons in the intricacies of delicate surgery [Ota 98]. In manufacturing, 3D SEs consisting of new prototype automobiles and the natural environment are being used to test new products before actual production [Schmeider 98]. Each of these application areas makes use of an

authoritative, three-dimensional digital representation of a given environment.

The Department of Defense (DoD) describes 3D SE in terms of the natural environment, including the terrain, oceans, atmosphere and space [DMSMP 95]. Terrain representation involves the composition and representation of the surface of the earth and of the natural and man-made features found there. Representation of the oceans includes the data describing the ocean bottom as well as changes in surface (e.g., sea-state) and sub-surface (e.g., pressure and acoustics) conditions. Atmospheric representations cover the zone from the earth's surface to the upper boundary of the troposphere. Some phenomena of interest there include atmospheric conditions such weather. The latter can also involve four-dimensional representations of natural conditions such as spatial location over time. Space representations cover the area beyond the upper boundary of the troposphere. In addition to representation of the physical environment, the 3D SE may also potentially involve the representation of natural or man-made processes at work in the natural environment, such as seasonal variation or the effects of man's interaction with his world.

This conception of a synthetic environment as a three-dimensional digital representation of the natural environment is not inconsistent with many uses in geographic information systems (GIS), city planning, etc. where accurate simulations of the natural environment and man's impact on the environment are essential. Users are provided with a means of examining the spatial relationships of digital objects that closely resemble their real world counterpart. The ability to model natural processes as well as man-made processes in relation to the natural environment can also be vital to understanding nature and man's impact on it.

Synthetic environment databases can also provide some degree of non-visual information about the environment called *topology* [USAS 98b]. Topology in this context refers to the explicit representation of the relationships between objects in the environment. This explicit, pre-computed definition of relationships avoids the need to computationally derive relationships at run-time. Topology means that a GIS application, for example, "knows" that a road allows travel in a certain direction. In some databases, the topological structures are lacking [MULT 96]. Image generator applications such as flight simulators do not necessarily need topological information. In other databases the topology is limited to the description of two-dimensional spatial relationships [VPF 96].

The remainder of this chapter provides introductory material about 3D synthetic environments. In order to provide a feel for what 3D SEs are and how they are used, Section 2 gives examples of some of the varied applications that make use of them. Following that, Section 3 examines

synthetic environment data sources and introduces various spatial databases used in the synthetic environment domain. The process by which this data is transformed into meaningful 3D SE databases is introduced in Section 4. Section 5 discusses 3D SE database repositories, interchange specifications and distributed simulation applications. The chapter concludes with a look at the technologies that are used for 3D SE visualization. These topics should provide good background material for readers who are interested in exploring this subject in greater detail.

2. 3D SYNTHETIC ENVIRONMENT APPLICATIONS

This section introduces examples of some of the different uses of 3D SEs, namely, in the areas of aerospace, city planning, education, manufacturing and M&S.

2.1 Aerospace

SEs have been used to train astronauts for Space Shuttle and International Space Stations missions. Figure 1 shows an example of a shared virtual environment in which trainees in the U.S. and Europe were able to practice replacing a solar array drive on the Hubble Telescope. The 3D SE consisted of models of the Hubble Telescope and the cargo bay of the space shuttle. Shared SEs are also in development for training astronauts for maintenance operations within the International Space Station. These uses reduce overall costs of training since trainees are not required to relocate to special facilities in distant countries [Loftin 98].

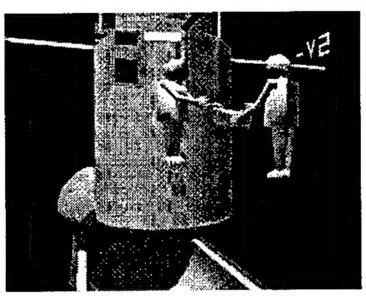


Figure 1. Repairs to the Hubble Telescope are Rehearsed in a Shared SE [Loftin 2000]

2.2 City Planning & GIS

The UCLA Urban Simulator shown in Figure 2 is an example of a SE developed for city planning. The Simulator links virtual reality technology with a more traditional Geographic Information System (GIS) database. The system allows planners and designers to evaluate urban development rapidly, in more detail and for less cost than traditional methods [Liggett 95]. Similar work on the use of SEs as a tool for city planning is reported in [Koninger 98] and [Tempfli 97].

Figure 2. UCLA Urban Simulator - Detailed Urban Model with Automated Vehicles and Pedestrians [Liggett 95]

2.3 Education

Project ScienceSpace is a collection of SEs that enable students to study the dynamics of motion, electrostatics and molecular structures [VETL 98]. In one example from that project, shown in Figure 3, objects are given behaviors consistent with their real world counterparts.

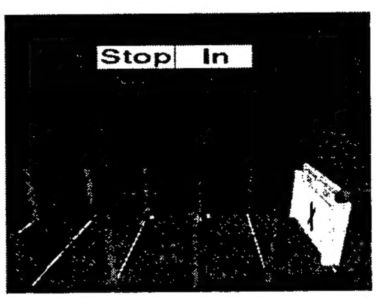


Figure 3. An Application Using a SE in Education [VETL 98]

2.4 Manufacturing

Daimler-Chrysler has used 3D SEs consisting of driving simulators to test new automobile designs. One of these is shown in Figure 4. The test driver sees the 3D SE consisting of the interior of the vehicle and the roadway in a Head Mounted Display. A correct visual impression of the vehicle is provided to the driver although he may only be sitting in a mock up simulator consisting of a seat, steering wheel, shift lever and pedals. Potential problems can be identified early in the development process long before the physical vehicle is built [Schmeider 98].

Figure 4. Daimler's Driving Simulator [Daimler 99]

2.5 M&S

SEs such as that shown in Figure 5 can provide a realistic simulation of a natural environment in which mission rehearsal and training can take place. Among the SE databases created for military M&S are:

- SAKI (Saudi Arabia, Kuwait and Iraq),
- STOW-E (Synthetic Theatre of War - Europe),
- Chorwon (Korea),
- Close Combat Tactical Trainer SE (based on an area in Central Europe but made to resemble the Midwestern U.S.),
- the Mission Training Support System SEs (geospecific SEs constructed from a helicopter pilot's point of view), and
- the Special Operations Forces Aircrew Training System SEs (supporting aircrew training and mission rehearsal) [Trott 96].

The views generated by each of these applications can vary with the needs of the user. An application for a ground vehicle simulation, for example, may provide detailed geometry about the terrain surface and 3D

objects on the terrain. Surface slope, soil mobility, the location and the size of obstacles may be provided in sufficient detail in the database so maneuverability could be determined at runtime. A flight simulator, in contrast, may require a texture-mapped image of the terrain instead of data about surface slope [Mamaghani 98]. Semi-Automated Forces (SAF) and Computer Generated Forces (CGF) are two applications that make use of topological information [Trott 96]. CGF entities are controlled by dynamic, reasoning software models, and 'react' to trainees' actions and the environment without operator input. SAF in contrast accepts some input from a human operator during the interaction with the trainee.

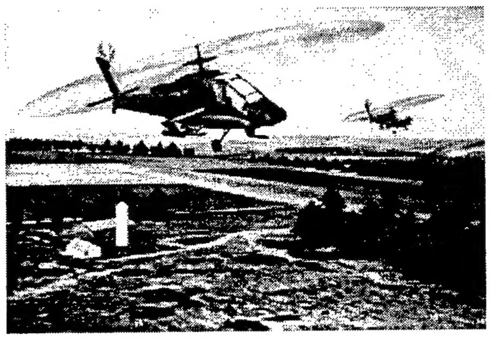


Figure 5. View of a Conceptual M&S SE [ES 99]

3. SYNTHETIC ENVIRONMENT DATA

3.1 Data sources

NIMA is the primary source of synthetic environment data for the Department of Defense and the private sector. In the 1980's NIMA began the process of transforming their paper mapping data to digital format with a new database specification, Vector Product Format (VPF). Generally, VPF separates data into thematic coverages, with each of these coverages containing thematically consistent data [VPF 96]. More details on VPF are given below.

A detailed listing of NIMA's digital data is available in [NIMA]. Table 1 lists NIMA's VPF products. Each product is designed to fill different needs. Digital Nautical Chart (DNC) for example, is directed at marine navigation and GIS applications, and it contains significant features collected from harbor, approach, coastal and general charts. Digital Topographic Data

(DTOP) is produced for specific geographic areas and consists of thematic layers from terrain analysis and topographic line maps. Themes include vegetation, transportation, surface materials, surface drainage, obstacles, surface configuration or slope, hydrography, boundaries, population, industry, physiography, utilities and data quality.

Table 1. A Partial Listing of NIMA's VPF Products

Name	Abbreviation
Digital Nautical Chart	DNC
Digital Topographic Data	DTOP
Interim Terrain Data	ITD
Vector Map	VMAP
Urban Vector Map	UVMAP
World Vector Shoreline	WVS
Tactical Terrain Data	TTD
Foundation Feature Data	FFD

Tactical Terrain Data (TTD), consisting of DNC, DTOP and Digital Terrain Elevation Data (described below), is intended to provide data critical to planning and executing joint operations such as close air support missions, amphibious operations and land combat operations. TTD is supportive of constructing SE databases that are to be used for terrain visualization, mobility planning, site and route selection, reconnaissance and communications planning, navigation and munitions guidance. TTD data density is generally consistent with similar portrayals on topographic line maps, terrain analysis products and hydrographic charts.

Interim Terrain Data (ITD) was designed to provide digital terrain analysis data for systems fielded before the production of Tactical Terrain Data. It consists of six thematic coverages or layers: vegetation, obstacles, transportation, and surface material, slope and drainage. Features correspond to a 1:50,000-scale map [NIMA, USAS 98a].

Vector Map (VMAP) is provided in Levels 0, 1 and 2, each increasing from small to large scale. Data coverages include boundaries, elevation, hydrography, industry, physiography, population, transportation, utilities, and vegetation. Urban Vector Map (UVMAP) provides specific vector-based geospatial data with city graphic content. The same coverages are provided as for VMAP. Detail is similar to NIMA city graphic and military city map products.

World Vector Shoreline (WVS) content includes shoreline, international boundaries, maritime boundaries and country labels. Five libraries provide data derive from 1:250,000 to 1:12,000,000 scale source. Bathymetric data is found in Digital Bathymetric Data Base (DBDB). DBDB is gridded data giving ocean depths in meters worldwide for each 5 minutes of latitude and longitude.

A primary source of terrain elevation data is NIMA's Digital Terrain Elevation Data (DTED). DTED comes in several resolutions ranging from 100 meter (Level 1) to 30 meter (Level 2) and down to 1 meter (Level 5). DTED is formatted in a uniform matrix of terrain elevation values, in 1° by 1° cells identified by southwest corner coordinates. This provides elevation data source for SE systems that require landform, slope, elevation or gross terrain roughness. While DTED is a prime source of terrain elevation data, Digital Feature Analysis Data (DFAD) is a prime source of digital feature data. DFAD is assigned an identification code and is described in terms of height, composition, length and orientation. DFAD is collected from photogrammetric as well as cartographic source material. DFAD Level 1 offers medium scale detail (1:250,000) and Level 2 offers higher scale (1:50,000). The types of features included in DFAD include roads, railways, drainage, prominent buildings in urban areas, and prominent towers and power lines.

In addition to its vector-based products, NIMA also provides other synthetic environment data in raster format. These include Arc second Raster Chart/map (ARC) Digitized Raster Graphics (ADRG) and ARC Digital Raster Imagery (ADRI). ADRG is a digital raster representation of paper cartographic products. In contrast, ADRI is produced from orthorectified panchromatic SPOT commercial imagery.

3.2 NIMA's vector product format data model

VPF was developed by NIMA as a specification for large geographic databases. The VPF data model is organized as shown in Figure 6. A VPF database is made up of libraries. Libraries are organized into coverages of thematically consistent data that share a single coordinate system and scale and that are contained within a specified spatial extent. Each coverage is then composed of features whose primitives maintain topological relationships according to one of the four levels of topology found in VPF.

VPF supports the *tiling* of coverages. Tiling is the practice of geographically subdividing coverages for the purpose of improving data management. The subdivided coverage is referred to as a tiled coverage. A tiling scheme defines tile boundaries, the size of tiles and the handling of the features that lie on tile boundaries and text primitives that cross boundaries. Tiling schemes are defined by product specifications rather than by VPF. If any of the coverages in a library are tiled, then all coverages must either use the same tiling scheme or be untiled. Edges and faces that either lie on or cross tile boundaries and connected nodes that lie on tile boundaries take part in cross-tile topology. The primitives in each tile of a tiled coverage are handled separately from primitives in other tiles. This results in each

primitive having an id that is unique only within the tile. Cross-tile topology utilizes a triplet id consisting of the primitive's id in the current tile, the id of the bordering tile and the id of the continuing primitive in the bordering tile.

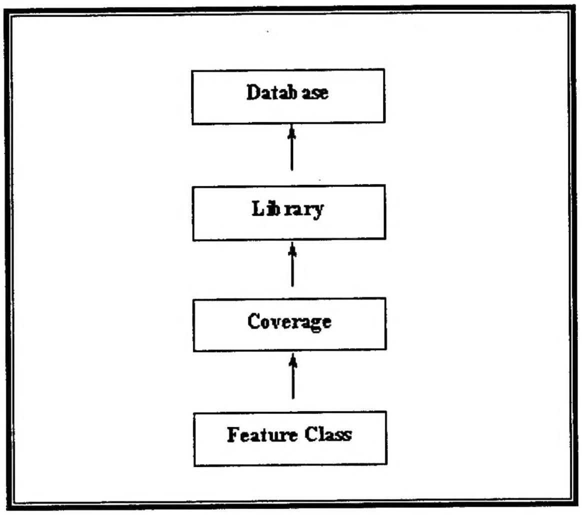


Figure 6. VPF Top Level Data Model

Five categories of cartographic features are defined in VPF: Point, Line, Area, Complex and Text. Point, Line and Area features are classified as Simple Features composed of only one type of primitive. Each Simple Feature is of differing dimensionality: zero, one and two for Point, Line and Area Features respectively. Unlike Simple Features, Complex Features can be of mixed dimensionality, and are obtained by combining Features of similar or differing dimension. The VPF feature class structural schema is shown in Figure 7 below.

The five VPF spatial primitives are:

1. *Entity node* – representing isolated features;
2. *Connected node* – endpoints defining edges;
3. *Edge* – an arc representing a linear feature or a border of a face;
4. *Face* – a two-dimensional primitive representing area features such as an area of terrain; and
5. *Text* - a cartographic primitive that allows the representation of names associated with ill-defined regions.

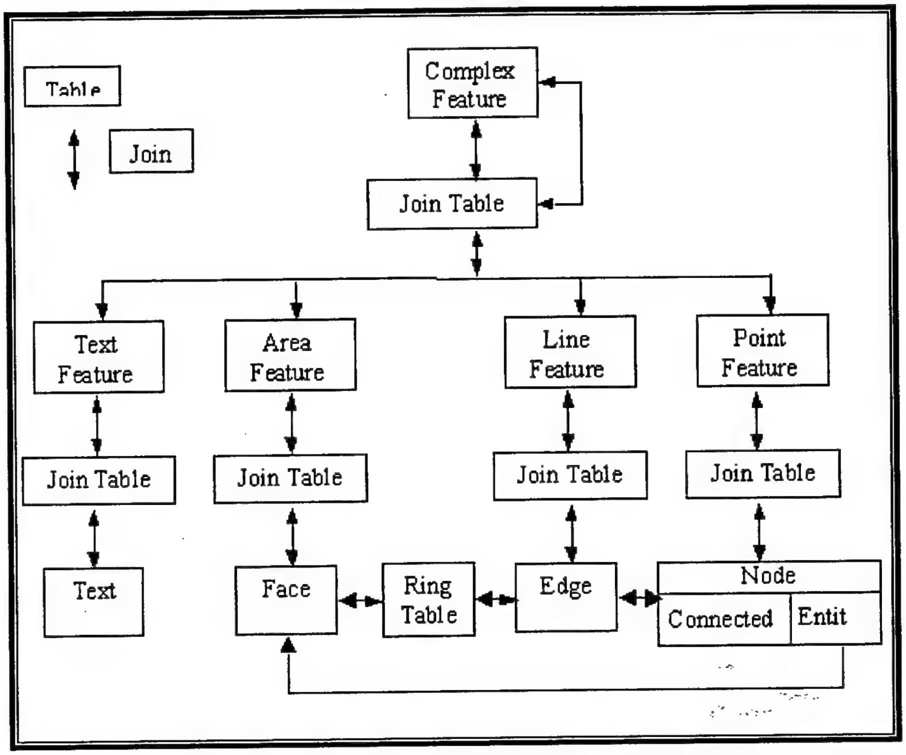


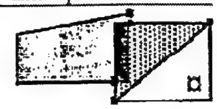
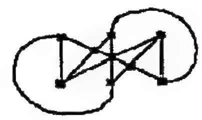
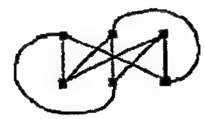
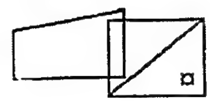
Figure 7. VPF Feature Class Structural Schema

A mandatory Minimum Bounding Box (MBB) table is associated with each edge and face primitive. The simple shape of the MBB makes it easier to handle than its corresponding primitive. The edge and face primitives have an optional *spatial index*. The spatial index is based on a binary tree, which reduces searching for a primitive down to binary search. Due to its variable length records, the connected node table has a mandatory associated *variable length index*.

VPF associates the face table with a *ring* table, which identifies the ring forming the outer boundary of each face primitive together with all internal rings of each face primitive. This table allows (along with the face table) the extraction of all of the edges that form the outer boundary and the internal rings of a face primitive. For more information, the interested reader is referred to the VPF specification [VPF 96].

VPF provides four levels of topology shown in Table 2. These range from Level 0, containing no explicit topological information, to Level 3 which explicitly represents all topological connections.

Table 2. VPF Levels of Topology. [VPF 96]

Level	Name	Primitives	Description	Example
3	Full topology	Connected nodes, entity nodes, edges and faces.	The surface is partitioned by a set of mutually exclusive and collectively exhaustive faces. Edges meet only at nodes.	
2	Planar graph	Entity nodes, connected nodes and edges.	A set of edges and nodes where, when projected onto a planar surface, the edges meet only at nodes.	
1	Non-planar graph	Entity nodes, connected nodes and edges.	A set of entity nodes and edges that may meet at nodes.	
0	Boundary representation (spaghetti)	Entity nodes and edges.	A set of entity nodes and edges. Edges contain only coordinates, not start and end nodes.	

3.3 Commercial database formats

Many commercial systems use VPF data possibly along with data from other sources such as field surveys to create 3D SE databases. Loral Advanced Distributed Simulation, Inc. (Loral), Lockheed Martin Information Systems (LMIS), Multigen, Inc., Evans & Sutherland (E&S) and Lockheed Martin Tactical Defense Systems (LMTDS) are major developers of synthetic environment database systems. Their products include database formats such as the S1000, OpenFlight, TARGET, Integrator and specific image generator formats. Some of these are described below.

The S1000 database is a Loral product. It's one of the formats used by the U.S. Army Topographic Engineering Center (TEC), Digital Products Center (DPC) to develop 3D terrain databases [Trott 96]. Many other database formats are then compiled from the final S1000 database. Details of the S1000 are set forth in [Farsi 95]. The S1000 is generally organized around four major blocks of data: land models (3D polygons), unique static object models (3D polygons including the geometry of buildings, trees, vehicles, targets, etc.), generic model references (2D point data), and 2D network references. The first three are organized into quadtrees, while the last is organized into a linear array of filenames, which in turn reference individual files. Features such as treelines and canopies are stored as

attributed 2D vector data, that in turn is used to generate 3D polygonal geometry which conforms to the underlying terrain. Textures and generic models are stored in libraries, which are referenced by the database, but not technically part of the database. In the S1000 database, polygons are 3 or 4 sided, convex and planar, and are the lowest level geometric entity. Model polygons are stored in the local coordinate system of the model (model coordinates), while all other polygons are stored in the database's world coordinates. Among the many polygons attributes are mobility types, color, thermal properties, how it should be colored (face, vertex or textured), and shading.

LMIS's TARGET product [LMIS 99a] is organized around one or more roots, which can be either a defined 'gaming area' or a 'moving model.' The gaming area is composed of one or more 'common geographic databases' and other optional data such as a terrain grid, texture image, project control information, etc. The common geographic database is composed of one or more 'core images' and header information. Core images are in turn organized into attribute, feature and vertex tables. TARGET defines 14 different types of features, significantly more than S1000 and VPF [VPF 96]. Among these are topographic polygon, topographic point and topographic line, base terrain, blended terrain and continuous terrain, terrain shadow, surface culture, radar point and radar line, and model reference. Each feature is associated with a list of vertices that define the feature. As with the S1000 database, TARGET also provides for a model library. In addition to being a database format, TARGET provides tools that enable the automated processing of standard NIMA data (such as DTED and DFAD) and of two interchange formats SIF and SEDRIS (discussed below). A toolkit also allows capture of detail from imagery and maps for inclusion within the database. When data from different sources might otherwise result in an inconsistent representation of the real world, TARGET fuses these into a consistent world model [LMIS 99b].

In contrast to S1000 and TARGET, MultiGen's OpenFlight has a much simpler database organization. OpenFlight's design, described in [Mult 96], organizes the database in a hierarchy of logical groupings. A database file header points to a 'group' or logical subset of a database. This structure allows all nodes in the group to be manipulated as a single entity. Group nodes in turn point to other groups, objects or level-of-detail nodes. Level-of-detail nodes are conceptually similar to the group node, but act as a switch to allow the display of everything below it to be turned on or off depending on range from the viewer. OpenFlight 'objects' contain a logical collection of polygons. Objects can also point to another object, to a group, to a level-of-detail node or to a polygon. The polygon, in turn, contains an ordered set of vertices, and is attributed with color, texture, materials,

transparency, etc. Vertices contain a 3D coordinate and can have vertex normals and texture mapping attribution. OpenFlight also provides tools to generate terrain polygons from DTED, to convert DFAD automatically into a 3D visual scene, to construct roads, and to import SIF (discussed below) data [TEC 99]. OpenFlight emphasizes visual representation, not topological relationships.

3.4 Three-dimensional data acquisition

VPF synthetic environment related data often lacks the geometry necessary to reconstruct detailed three-dimensional objects in a 3D SE. VPF, for example, generally represents a building as a two-dimensional polygon. Much of the geometric detail and texture data necessary to reconstruct a realistic-looking 3D building that closely resembles its real-world counterpart is omitted.

There is on going research into the automated extraction of this type of 3D feature data from imagery. Many of these methods use photogrammetric techniques such as shadow analysis and line-corner analysis to automate the identification and extraction of 3D man-made features from high-resolution imagery [Irvin 89, Roux 94]. In addition to establishing the geo-location and the shape of the features, heights can be approximated, and the results can be used to generate 3D views. More recent work has made use of a combination of data from airborne laser scanning, color imagery and high-resolution 2D maps [Haala 99a, Haala 99b]. Other efforts are devoted to developing fully textured 3D models of features from digital video imagery [Geometrix 2000].

Many 3D models are created for SEs using packages such as TARGET [LMIS 99b] and OpenFlight [MULT 96]. Digitized building blueprints, when available, can provide highly accurate 3D structural detail in a relatively short period of time.

4. THE SYNTHETIC ENVIRONMENT DATABASE GENERATION PROCESS

NIMA produces its VPF formatted synthetic environment data in segmented thematic coverages. This data organization generally follows historic mapping techniques of organizing data in disjoint thematic layers, which are overlaid to produce the desired map view of the world. In contrast, the development of a realistic detailed SE requires the integration of these data sources and considerable data processing. DTED, DFAD and ITD, for example, are produced by different processes from different

sources, and do not always correlate very well [Trott 96]. Transportation networks, buildings and other 3D features must be integrated with 3D terrain elevation data to produce 3D synthetic environment databases. Roads, for example, existing only as one-dimensional features in VPF must be widened to their real-world width, and simply draping roads over 3D terrain does not assure a reasonable pitch [Abdelguerfi 97].

Specific approaches to the creation of a SE may vary based on available tools, system requirements, application specific needs, etc. The process basically follows the flow chart shown in Figure 8 below and can be described in terms of data collection, terrain skin creation, model creation and data integration. This is described in detail in [Abdelguerfi 97, Abdelguerfi 98, Mamaghani 98, Trott 96] and will only be outlined here.

DATA COLLECTION: Data collection involves identification and collection of relevant data such as DTED, DFAD, ITD, etc. It also involves supplementing NIMA digital data with digital imagery and cartographic data as may be necessary. In addition, where NIMA data may lack the necessary attribution (such as real-world appearance of a point feature), on-site surveys may be necessary.

TERRAIN MODEL CREATION: Terrain models typically fall into one of three categories: Grid, Triangulated Irregular Network (TIN) or Constrained TIN. The Grid model utilizes a rectangular grid with the data points at the intersection of the grid intervals used to identify terrain elevation. Elevation values must be interpolated in the event no values coincide with the grid intervals. A higher data density (or finer mesh) is required to achieve precision with rough surfaces. Grid models cannot accurately represent surface features that are smaller than the given point spacing of the grid. With a 250-meter wide grid interval, for example, a 50-meter wide feature must either be omitted or must be represented as 250 meters wide. A TIN, in contrast, approximates the surface by means of a network of planar, non-overlapping and irregularly shaped triangular facets, with the vertices of each triangle located at the data elevation points [Floriani 87]. They can approximate any surface at any level of accuracy with a minimal number of polygons [Scarlatos 90]. A constrained TIN is constructed by using significant line segments obtained from feature data in the triangulation process. The line segments can be part of a significant surface feature such as a building footprint, transportation network or lakeshore, and are considered to have reliable elevation attributes. This assures, for example, that roadways will have reasonable pitch, that buildings will not float above the terrain or be buried beneath it and that waterway surfaces will have uniform elevation.

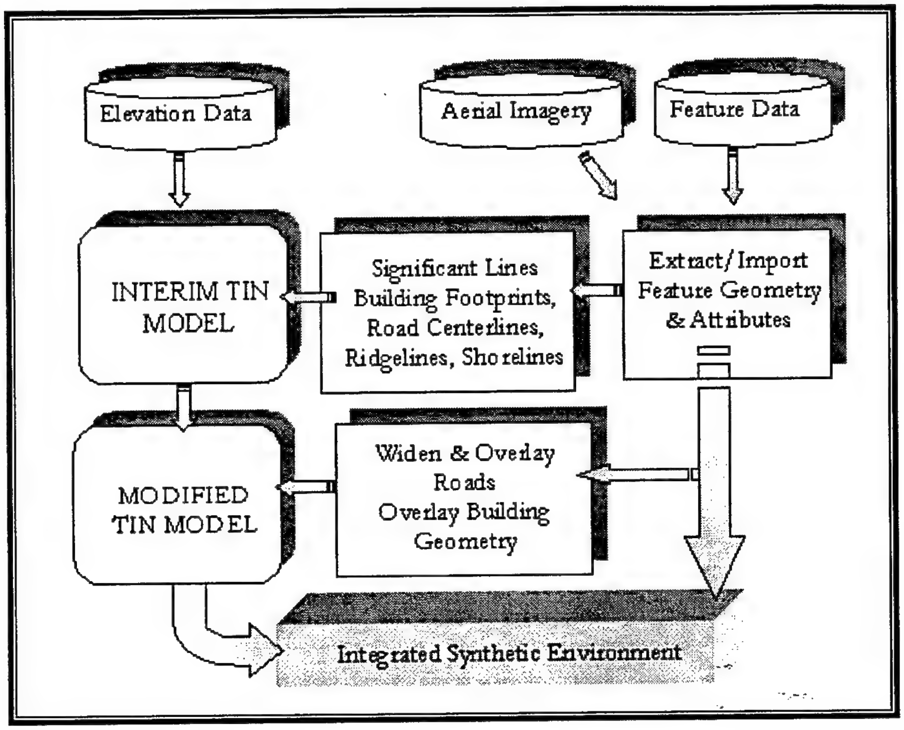
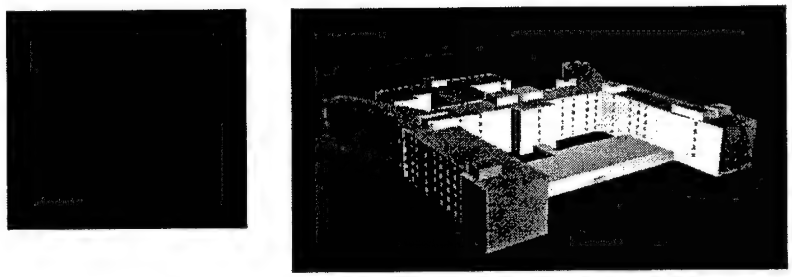


Figure 8. Flow Chart of 3D Synthetic Environment Creation

GENERIC/SPECIFIC 3D MODEL CREATION: VPF data provides at most two-dimensional symbolic representation of features [VPF 96]. This requires that three-dimensional models be imported from already existing sources, constructed as specific replications of features or constructed as generic feature models. For example, a bridge may be represented as a line in VPF with attribution indicating that it is a bridge. A polygon may be used for the representation of the footprint of a building, with attributes such as height and building composition. Figure 9 shows an example of a typical 2D symbolic representation of the building as might be found in a VPF database alongside a 3D model of the same building as might be found in a 3D SE.



Traditional Representation 3D Object Model

Figure 9. Two Views of the U.S. Public Health Service Hospital located at the Presidio, San Francisco, California [Ladner 2000]

DATA INTEGRATION: In addition to constructing three-dimensional models, feature data may also have to be conformed to the underlying terrain. This may involve integrating the feature models with the terrain skin, translating the models to the correct location, or thinning features that are too numerous for the scale of the SE. Edge matching may also be an issue, as feature data obtained from different coverages may not have consistent edge information. Realistic texture or color may also be applied.

5. SYNTHETIC ENVIRONMENT DATABASE EXCHANGE, RE-USE AND SHARING

SE databases are costly and time consuming to produce, and there are many proprietary data models and formats in use. The ability to reuse data from existing SE databases to build new SE databases for new applications is desirable. Data repositories and database interchange specifications are two means of accomplishing this.

5.1 Data Repositories

Data repositories and clearing houses hold SE data in a centralized location or make the availability of data at different locations known to prospective users. Such data sources include the Terrain Resource Repository (TRR), the Master Environmental Library (MEL), the Tactical Oceanography Wide Area Network (TOWAN), the National Geospatial Data Clearinghouse (NGDC), and the National Oceanographic and Atmospheric Administration Server (NOAA).

The TRR is maintained by NIMA's Terrain Modeling Project Office (TMPO). The TRR provides Internet access to various terrain data products available from the Department of Defense [TMPO 2000]. Users can access samples of many of NIMA's standard data products, along with software for viewing. The TRR also provides links to numerous web sites that are sources for environment data. Among these are data sources maintained by state agencies, the U.S. Geologic Survey, the National Oceanographic and Atmospheric Administration, the U.S. Census Bureau, the U.S. Department of Transportation, the U.S. Department of Agriculture, the Bureau of Land Management, the Canadian Government, and the United Nations.

The Defense Modeling Simulation Office (DMSO) maintains MEL. MEL indexes environmental data source location. Through MEL, users can locate and order SE data online [MEL 2000].

TOWAN is provided by the Naval Research Laboratory at Stennis Space Center as an online environmental data repository and server that allows Department of Defense personnel and their contractors to search for and retrieve environmental information. TOWAN makes oceanographic databases available, including bathymetric, geoacoustics, ice and magnetics. TOWAN is one of the nodes in MEL [TOWAN 2000].

The NGDC aggregates over 100 spatial data servers and provides a search interface. Search options include location, time period of content, full text and fielded search using country names or U.S. placenames. A custom search allows users to define parameters including map, temporal and server [NGDC 2000].

The NOAA Server provides an on-line search by area-of-interest access to several databases. These databases include the NOAA Central Library, the Japan Science and Technology Corporation, the Foreign Data Library, the Office of Oceanographic and Atmospheric Research, the National Weather Service, and the National Snow and Ice Data Center [NOAA 2000].

5.2 Interchange specifications

While centralized data repositories and clearing houses afford the means of making the existence of synthetic environment data known to prospective users, data interchange specifications resolve some of the problems that may arise from importing that data into the user's native format. Two such specifications are the Standard Simulator Database (SSDB) Interchange Format (SIF), also known as Project 2851 [SIF 93] and the Synthetic Environment Database Specification and Interchange Specification (SEDRIS) [SEDRIS 2000]. SEDRIS, for example, specifies a data model, which defines a standard representation of the SE and serves as an

intermediary between the major existing proprietary products by providing an API for exporting to and importing from and from those products.

5.3 Distributed Simulations of Synthetic Environments

While tools such as SEDRIS have been developed in order to foster the interchange of SE data, other technologies exist that enable distributed simulations of synthetic environments. These include Distributed Interactive Simulation and High Level Architecture [Dahmann 99, Davis 95, Hofer 95, and HLA 98]. These technologies establish connectivity between independent workstations to create a consistent SE with respect to perception and behavior. Distributed interactive simulations of SEs have been noted to be beneficial to training. Trainees can interact together in a common synthetic environment space. Insights can be gained about processes involving human interactions, behavior and decision making. Although distributed interactive simulation technologies have primarily evolved in the M&S arena, they may prove to benefit any distributed simulation application whether it involves training, research, prototyping products, etc.

6. SYNTHETIC ENVIRONMENT VISUALIZATION TECHNOLOGIES

This section reviews some of the existing technology used for visualizing SEs. These typically provide the user with some degree of immersion into the environment depending on the application. That may involve a computer screen display in which the user can *walk* across the terrain or *drive* an automobile on a real-world highway, or it may involve some of the more sophisticated immersive technologies discussed below. For added realism, the SE may provide sounds appropriate to the environment being modeled or provide haptic devices to give the user a physical sense of *touching* an object he is virtually touching through interaction with the SE.

6.1 The CAVE

The CAVE Automatic Virtual Environment, Figure 10, is a fully immersive projective system composed of a room constructed of large rear-projection screens on which graphics can be projected on the surfaces. A tracking system tracks the user's head and hand orientation and position. Users wear stereo shutter glasses. As the viewer moves inside the CAVE, the correct stereoscopic perspective projections are calculated based on the viewer's position [Pape 97].

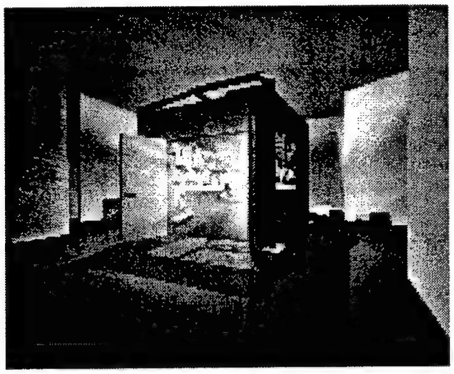


Figure 10. View of the CAVE [FSI 2000]

6.2 The Workbench

Also known as the Responsive Workbench or the Immersadesk, this device is a semi-immersive projective system based on a high-resolution tabletop display. Three-dimensional SEs are projected as stereoscopic images onto the surface of a table. As with the Cave, viewers wear stereo shutter glasses and a tracking device, which calculates the correct perspective image for each viewer's location. Tracking may be by way of magnetic, infrared or an inertial system. Interaction with the environment is by way of a stylus and gloves, each also equipped with special tracking devices. Systems enabling two-handed manipulations, shown in Figure 11, are possible [Cutler 97].

Figure 11. View of the Workbench [Cutler 97]

6.3 Head Mounted Displays

Head Mounted Displays (HMDs), Figure 12, fix monitors in front of the eyes usually blocking all views of the user's surroundings. When equipped with a tracking device, the user's view changes to a new perspective as he or she turns his or her head or moves forward/backward, providing a more interactive visual display.

Figure 12. View of a Head Mounted Display [LIC 2000].

6.4 Virtual Retinal Display

Figure 13 shows an example of the Virtual Retinal Display (VRD), which projects electronic information on the eye without the use of a screen. The image is conveyed by scanning an electronically encoded beam of light through the pupil to the retina. The user has the impression of viewing a high quality video image an arm's length away. VRD technology can be incorporated into a variety of small hand-held or head-worn devices. This technology has the advantage of not obstructing the user's view of his/her natural surroundings [Virre 98].

6.5 Monitors

Computer monitors may use more advanced stereoscopic techniques, but may also employ various software packages to enhance the normal two-dimensional windows. These rendering packages include OpenGl, Java3D, the Virtual Reality Modeling Language, Iris Performa, OpenInventor, etc.

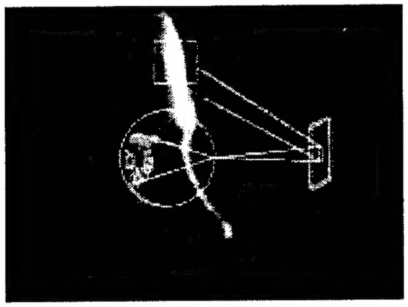


Figure 13. Virtual Retinal Display [MSVI 2000]

6.6 Haptics

Haptics provide a realistic sense of touch to users of SEs. Incorporated into gloves, haptics correlate what the user sees in the SE with what he should feel by providing a feedback stimulus to the user. Sandia National Lab's Cyberglove shown in Figure 14, for example, tracks the user's hand movements and finger orientation. It provides tactile sensations through vibrations transmitted by way of plungers within the glove that tap the user's fingertips [Villarreal 99].

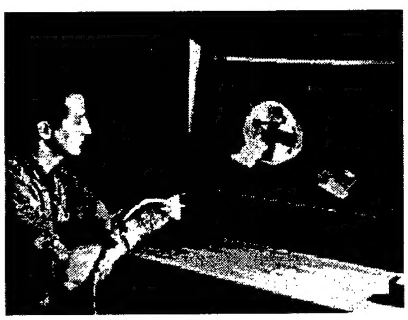


Figure 14. Sandia National Lab's Cyberglove [Villarreal 99]

7. CONCLUSION

This chapter has introduced three-dimensional synthetic environments by examining their uses, data sources, databases, database exchange mechanisms, distributed architectures and visualization technologies. These topics have been addressed from the standpoint of the 3D SE as a digital

representation of the natural environment. While 3D SEs have traditionally been associated with military M&S, they are being used in such diverse disciplines as education, urban planning and manufacturing. Although much synthetic environment source data is produced by the National Imagery and Mapping Agency, the process of constructing a 3D SE database is often a time consuming and costly process. The use of clearing houses and interchange specifications to exchange and re-use 3D SE databases is therefore desirable. Visualization of SEs can involve sophisticated devices such as the CAVE, Workbench or head mounted display, all providing the user with a sense of immersion into the environment, or merely a computer monitor running a 3D graphics program.

8. ACKNOWLEDGMENTS

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[Abdelguerfi 97] M. Abdelguerfi, E. Cooper, C. Wynne, K. Shaw, *An Extended Vector Product Format (EVPF) suitable for the representation of three-dimensional elevation in terrain databases*, Int. J. Geographical Information Science, Vol. 11, No. 7, 1997, pp. 649-676.

[Abdelguerfi 98] M. Abdelguerfi, R. Ladner, K. Shaw, *Terrain Database Generation*, 1998 American Society for Photogrammetry and Remote Sensing Annual Conference, Orlando, Florida, April 1998, pp.129-138.

[Birkel 97] P. A. Birkel, *SEDRIS Geospatial Reference Model*, http://www.sedris.org, July 10, 1997.

[Cutler 97] L. D. Cutler, B. Frohlich, P. Hanrahan, *Two Handed Direct Manipulation on the Responsive Workbench*, Proceedings 1997 Symposium on Interactive 3D Graphics, ACM SIGGRAPH, April 1997, pp. 107-114.

[Dahmann 99] J. S. Dahmann, *High Level Architecture for Simulation*, Defense Modeling and Simulation Office, Presentation September 1999.

[Daimler 99] Daimler Chrysler, http://www.daimlerchrysler.de/, December 1999.

[Davis 95] P. K. Davis, *Distributed Interactive Simulation in the Evolution of DoD Warfare Modeling and Simulation*, Proceedings of the IEEE, Vol. 83, No. 8, August 1995, pp. 1138-1155.

[DMSMP 95] Department of Defense, *Modeling & Simulation Master Plan*, DoD 5000.59-P, October 1995.

[ES 99] Evans and Sutherland, December 1999, http://www.evansandsutherland.com/

[Floriani 87] L. Floriani, *Surface Representations Based on Triangular Grids*, The Visual Computer, Vol. 3, 1987, pp. 27-50.

[FSI 2000] Fakespace Systems, Inc., April 2000.

[Geometrix 2000] Geometrix, Inc., http://www.geometrixinc.com/, January 2000.

[Haala 99a] N. Haala and V. Walter, Automatic Classification of Urban Environments for Database Revision using Lidar and Color Aerial Imagery. Joint ISPRS/EARSEL Workshop, Valladolid, 1999, pp. 76-82

[Haala 99b] N. Haala and C. Brenner, Virtual City Models from Laser Altimeter and 2D Map Data. Photogrammetric Engineering & Remote Sensing, Vol. 65, 7, 1999, pp. 787-795.

[HLA 98] IEEE P 1516.1, *HLA Interface Specification, Draft 1*, April 20, 1998.

[Hofer 95] D. C. Hofer, M.L. Loper, *DIS Today*, Proceedings of the IEEE, Vol. 83, No. 8, August 1995, pp. 1124-1137.

[Irvin 89] R. B. Irvin and D. M. McKeown, Jr., *Methods for Exploiting the Relationship Between Buildings and Their Shadows in Aerial Imagery*, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 19, No. 6, December 1989.

[Koninger 98] A. Koninger and S. Bartel, *3D-GIS for Urban Purposes*, GeoInformatica, Vol. 2, No. 1, March 1998, pp. 79-103.

[Ladner 2000] Roy Ladner, M. Abdelguerfi, and K. Shaw, *3D Mapping of an Interactive Synthetic Environment*, Computer, Vol. 33, No. 3, March 2000, pp. 35-39.

[LIC 2000] Liquid Image Corporation, http://www.liquidimage.ca/, January 17, 2000.

[Liggett 95] R. Liggett, S. Friedman, W. Jepson, *Interactive Design/Decision Making in a Virtual Urban World: Visual Simulation and GIS*, http://www.aud.ucla.edu/~friedman/esri/p308.html, Proceedings of the Fifteenth Annual ESRI User Conference. Palm Springs, CA, May 1995.

[LMIS 99a] Lockheed Martin Corporation, *Advanced Distributed Simulation Technology II (ADST II) Target/Sedris API (DO #0043) CDRL AB02 Sedris Mapping Document*, Lockheed Martin Information Systems, ADST II, P.O. Box 780217, Orlando, FL 32878, 1999.

[LMIS 99b] Lockheed Martin Corporation, *Compu-Scene TARGET*, Lockheed martin Information Systems, http://www.lmco.com/lmis/level4/target.html.

[Loftin 2000] R. Bowen Loftin, *Hands Across the Atlantic*, NASA/Johnson Space Center and University of Houston, reported at http://www.vetl.uh.edu/sharedvir/handatl.html, January 2000.

[Loftin 98] R. B. Loftin, *Distributed Virtual Environments for Collective Training*, Proceedings of the 1998 Image Conference, pp. RB1 - RB6.

[Mamaghani 98] F. Mamaghani, *Digital Illusion: Creation and Use of Synthetic Environments in Realtime Networked Interactive Simulation*, Clark Dodsworth, Jr., Contributing Editor, ACM Press, 1998, pp. 99-114.

[MEL 2000] Master Environment Library, Defense Modeling & Simulation Office, http://mel.dmso.mil, January 2000.

[MSVI 2000] Microvision, Inc., http://www.mvis.com/default.htm, April 2000.

[MULT 96] *OpenFlight Scene Description*, MultiGen, Inc., 550 S. Winchester Blvd., Suite 500, San Jose, CA 95128, Version 14.2.4, Revision A, January 1996.

[NGDC 2000] Federal Geographic Data Committee (FGDC) National Geospatial Data Clearinghouse (NGDC), http://www.fgdc.gov/, January 2000.

[NIMA] *Digitizing the Future*, National Imagery and Mapping Agency.

[NOAA 2000] National Oceanographic and Atmospheric Administration, http://www.esdim.noaa.gov/noaaserver-bin/NOAAServer, January 2000.

[Ota 98] D. Ota, B. Loftin, T. Saito, R. Lea, and J. Keller, *Virtual Reality in Surgical Education*, Virtual Environment Technology Laboratory, University of Houston, http://www.vetl.uh.edu/surgery/vrse.html, 1998.

[Pape 97] D. Pape, C. Cruz-Neira, M. Czernuszenko, *The CAVE User's Guide*, Electronic Visualization Laboratory, University of Illinois at Chicago, 851 S. Morgan St., Room 1120, Chicago, IL 60607-7053, 1997.

[Roux 94] M. Roux and D. M. McKeown, *Feature Matching for Building Extraction from Multiple Views*, Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 1994, pp. 46-53.

[Scarlatos 90] L. Scarlatos and T. Pavlidis, *Hierarchical Triangulation Using Terrain Features*, IEEE Conference on Visualization, 1990, pp.168-174.

[Schmeider 98] H. Schmieder, *Requirements for Virtual Reality Systems in Driving Simulation*, Proceedings of the 1998 Image Conference, pp. HJ1-HJ8.

[SEDRIS 2000] SEDRIS, http://www.sedris.org, 2000.

[SIF 93] Department of Defense, *Standard Simulator Data Base (SDDB) Interchange Format (SIF) Design Standard*, MIL-STD-1821, 17 June 1993.

[TEC 99] TEC, *Commercial Terrain Visualization Software Product Information*, U.S. Army Topographic Engineering Center, http:\\www.tec.army.mil/TD/tvd/survey/MultiGen.html, November 1999.

[Tempfli 97] K. Tempfli, Urban 3D Topologic Data and Texture by Digital Photogrammetry, Proceedings of the American Society for Photogrammetry and Remote Sensing, 1997, pp. 952-963.

[TOWAN 2000] Tactical Oceanography Wide Area Network, Naval Research Laboratory, Stennis Space Center, http://www7180.nrlssc.navy.mil/homepages/TOWAN/TOWAN.htm, January 2000.

[TMPO 2000] Terrain Resource Repository, Terrain Modeling Project Office, http://www.tmpo.nima.mil/mel, January 2000.

[Trott 96] K. Trott, *Analysis of Digital Topographic Data Issues in Support of Synthetic Environment Terrain Data Base Generation*, TEC-0091, U.S. Army Corps of Engineers, Topographic Engineering Center, November 1996.

[USAS 98a] U.S. Army Simulation, Training, and Instrumentation Command, Orlando, Florida, *SEDRIS and The Synthetic Environment Domain, Volume 1 of the SEDRIS Document SET*, 12350 Research Parkway, Orlando, FL, March 28, 1998.

[USAS 98b] U.S. Army Simulation, Training, and Instrumentation Command, Orlando, Florida, *Synthetic Environment Data Representation and Interchange Specification Overview, Volume 2 of the SEDRIS Documentation Set*, 12350 Research Parkway, Orlando, FL, March 28, 1998.

[VETL 98] Virtual Environment Technology Laboratory, University of Houston, Project Science Space, http://www.vetl.uh.edu/ScienceSpace/ScienceSpace.html, 1998.

[Villarreal 99] Q. Villarreal and P. Venkatesan, *Virtual Reality*, Sandia National Laboratories, http://www.ca.sandia.gov/VR/, November 1999.

[Virre 98] E. Virre, H. Pryor, S. Nagata, and T. A. Furness, *The Virtual Retinal Display: A New Technology for Virtual Reality and Augmented Vision in Medicine*. In Proceedings of Medicine Meets Virtual Reality, San Diego, California, USA, Amsterdam: IOS Press and Ohmsha, 1998, pp. 252-257.

[VPF 96] Department of Defense, *Interface Standard for Vector Product Forma*, MIL-STD 2407, 28 June 1996.